Space and the Environment: Balancing Scientific Exploration and Environmental Protection

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Abstract

Space exploration carries immense scientific, technological, and inspirational value, yet the propulsion systems, spacecraft, and infrastructure it depends on leave a measurable footprint on both outer space and Earth. Orbital debris, atmospheric pollutants from launches, and the risk of biological contamination of celestial bodies now pose direct threats to the long-term viability of the very activity that produces them. This article examines the tension between scientific exploration and environmental protection in space, situating it within existing legal frameworks — principally the Outer Space Treaty of 1967, the Liability Convention, the Moon Agreement, and the non-binding UN Space Debris Mitigation Guidelines, alongside emerging soft-law and industry initiatives such as COSPAR’s Planetary Protection Policy, the Artemis Accords, and the World Economic Forum’s Space Sustainability Rating. It argues that the absence of a binding legal definition of “space debris,” combined with the voluntary character of existing mitigation guidelines, has produced a governance gap that disproportionately disadvantages developing and emerging space-faring states, which lack the resources to absorb the costs of a purely self-regulating regime. Drawing on recent technological developments like green propulsion, reusable launch vehicles, active debris removal, and in-orbit servicing, the article contends that technological innovation alone cannot substitute for binding international regulation, and that the two must develop in tandem. It concludes with concrete recommendations for treaty reform, mandatory debris mitigation standards, and capacity-building mechanisms aimed at ensuring that outer space remains, in the language of the Outer Space Treaty, the “province of all mankind” rather than a common resource degraded by the states best able to exploit it first.

*Keywords**:** space law; space debris; planetary protection; space sustainability; Outer Space Treaty; environmental law; Artemis Accords*

1. Introduction

1.1 The Allure and the Cost of Space Exploration

Space exploration has become one of humanity's most transformative scientific endeavors, driving technological innovation, expanding knowledge of the universe, and contributing significantly to socioeconomic development. From satellite technology that supports communication, weather forecasting, disaster management, precision agriculture, and climate monitoring to ambitious missions aimed at lunar and planetary exploration, the benefits of space science have extended far beyond astronomical discovery. However, the rapid expansion of space activities has also raised growing environmental concerns both on Earth and in outer space. Rocket launches contribute to greenhouse gas emissions, black carbon deposition in the upper atmosphere, and localized environmental pollution, while increasing amounts of orbital debris threaten the long-term sustainability of space operations. The extraction of natural resources for spacecraft manufacturing, the environmental footprint of launch facilities, and the potential ecological implications of future extraterrestrial resource exploitation further underscore the complex relationship between scientific advancement and environmental stewardship.

Consequently, achieving a balance between scientific exploration and environmental protection has become a critical global challenge that requires sustainable policies, international cooperation, and environmentally responsible technological innovation. Guided by international frameworks such as the Outer Space Treaty and the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS), contemporary space governance increasingly emphasizes sustainable space activities that minimize environmental impacts while preserving the benefits of scientific discovery for future generations. Therefore, the concept of balancing scientific exploration with environmental protection represents a fundamental principle for ensuring that humanity's pursuit of knowledge beyond Earth does not compromise the ecological integrity of either the terrestrial or space environment, making it an important area of inquiry for researchers, policymakers, environmental scientists, and space agencies alike.

Space - the final frontier, beckons with promises of discovery, adventure, and the expansion of human knowledge. From Yuri Gagarin’s historic orbit to the Mars rovers’ tireless exploration and the James Webb Space Telescope’s early images of the deep universe, humanity’s fascination with the cosmos persists undiminished.[1] Yet every rocket launch, satellite deployment, and extraterrestrial mission leaves an imprint. Space debris clutters Earth's orbit, and lunar and Martian landings disturb pristine, scientifically valuable landscapes.

Debris is no longer a marginal concern. Active missions already have to plan around it: NASA's own conjunction-assessment guidance treats a relative closing speed in excess of 10 km/s in low Earth orbit (LEO) as routine, and defines a threshold of specific kinetic energy above which a collision is expected to be catastrophic for the smaller of the two objects involved.[2] The accumulation of defunct human-made objects in orbit derelict spacecraft, mission-related debris, and fragmentation debris imposes what is, in effect, an externality: the cost of the risk created by one actor's launch or operational decisions is borne by every other operator sharing that orbital regime.[3] This debris endangers active spacecraft and raises the probability of catastrophic collisions that generate still more debris.

As exploration extends further beyond the Moon, to Mars, and eventually to asteroids the twin obligations become inseparable: to safeguard the target bodies from contamination, and to safeguard Earth from whatever those missions might return. Preserving pristine, potentially habitable environments is essential to understanding both the universe's origins and Earth's own evolutionary history.[4] As J. Lederberg and D. B. Cowie observed as early as 1958, in a passage

[1] In 2021, the launch of the James Webb Space Telescope was delayed by two days shortly before liftoff; contrary to some secondary reporting, this delay was caused by a communication fault between the observatory and its Ariane 5 launch vehicle, not by a debris-collision risk. See NASA/Associated Press, "NASA: Webb Telescope Launch Delayed by Communication Problem" (14 December 2021) https://phys.org/news/2021-12-nasa-webb-telescope-problem.html accessed 11/7/26. [Author's note: the original manuscript attributed this delay to a space-debris collision risk. I could not verify that claim against contemporary reporting and have corrected it here; please confirm before submission.]

[2] NASA Orbital Debris Program Office, "Process for Limiting Orbital Debris," NASA-STD-8719.14; see also discussion of conjunction-assessment thresholds in current orbital-debris engineering literature.

[3] Ferreira-Snyman A, "Outer Space Exploration and the Sustainability of the Space Environment – An Uneasy Relationship" *PER/PELJ* 2023(26), DOI: 10.17159/1727-3781/2023/v26i0a14960, accessed 13/4/24.

[4] Coustenis A, Hedman N, Doran PT, Al Shehhi O, Ammannito E, Fujimoto M, Grasset O, Groen F, Hayes AG, Ilyin V, Kumar KP, Morisset C-E, Mustin C, Olsson-Francis K, Peng J, Prieto-Ballesteros O, Raulin F, Rettberg P, Sinibaldi S, Suzuki Y, Xu K and Zaitsev M, "Planetary protection: an international concern and responsibility" (2023) 10 *Front. Astron. Space Sci.* 1172546, DOI: 10.3389/fspas.2023.1172546, accessed 13/4/24.

that has lost none of its force, "[w]e are in the awkward situation of being able to spoil certain possibilities for scientific investigations for a considerable interval before we can constructively realize them . . . we urgently need to give some thought to the conservative measures needed to protect future scientific objectives on the Moon and the planets."[5] The imperative, then, is twofold: not to destroy space as we explore it, and to exercise equal care over what we bring back to the only inhabited planet we know of.

Public attitudes toward this trade-off are not settled. Surveys show that people value scientific progress and environmental preservation simultaneously, yet public sentiment toward space activity oscillates between romanticism and pragmatism some regard it as a noble collective quest, others question its cost and ecological toll. Astronauts, for their part, frequently describe the "overview effect": a marked shift in perception that follows from seeing Earth as a single, fragile object from space. Whether that perspective can be translated into durable environmental policy, rather than remaining a private epiphany, is one of the underexplored questions this article returns to in its concluding recommendations.

This article proceeds as follows. Section 2 sets out the case for space exploration and its demonstrable contributions to sustainable development on Earth. Section 3 examines the environmental costs of that same activity, with particular attention to orbital debris, atmospheric pollutants, and contamination risk. Section 4 analyses the legal and institutional gaps that leave much of this harm inadequately regulated. Section 5 surveys existing planetary protection and debris mitigation policies. Section 6 reviews emerging technological and institutional innovations. Section 7 concludes with specific, actionable recommendations for reform.

2. The Case for Space Exploration: Contributions to Sustainable Development

Space exploration is not merely a scientific indulgence; it is a significant driver of sustainable development on Earth. Its principal contributions include:

[5] Lederberg J and Cowie DB, "Moondust; the study of this covering layer by space vehicles may offer clues to the biochemical origin of life" (1958) 127(3313) *Science* 1473, DOI: 10.1126/science.127.3313.1473.

1. **Advancing scientific knowledge**: Better understanding of the universe, including the discovery of exoplanets and insights into the origins of stars and galaxies.
2. **Expanding our understanding of life**: Insight into the origins and development of life in the cosmos, with implications for astrobiology and, potentially, the discovery of extant or extinct extraterrestrial life.
3. **Technological advancement**: Innovations developed for space missions routinely find terrestrial application: lightweight materials with uses in the automotive and aviation industries, and GPS, originally a military technology, now embedded in daily civilian life. Space research has also advanced medical knowledge.
4. **Earth monitoring and environmental management**: Satellite-based Earth observation underpins accurate weather forecasting, land-use planning, and disaster management, with direct economic value: better prediction of hurricane paths, for instance, improves evacuation planning and resource allocation.[6]
5. **Educational and inspirational impact**: Space exploration inspires participation in science, technology, engineering, and mathematics (STEM), fields that are recognized drivers of long-run economic growth.
6. **Resource utilization**: Asteroid mining, while still speculative at commercial scale, holds promise for elements such as platinum-group metals that are scarce on Earth but comparatively abundant in certain asteroid classes, with potential implications for electronics and renewable-energy supply chains.
7. **Planetary defense**: A functioning space programme remains the only realistic means of detecting and, if necessary, deflecting a hazardous near-Earth object before it strikes Earth.

[6] "The Economic Value of Space Exploration – A Quick Overview" https://newspaceeconomy.ca/2023/10/07/the-economic-value-of-space-exploration-a-quick-overview/ accessed 13/4/24.

8. **Sustainable-living expertise transfer**: Techniques developed for closed-loop life support and resource-constrained habitation on future planetary outposts have direct application to sustainable urban planning on Earth.

9. **Economic benefits**: The global space industry now exceeds an estimated USD 400 billion in value and continues to grow, generating high-skilled employment, cross-sector innovation, and diplomatic partnerships that often translate into broader economic cooperation.[7]

Space-based technologies and services that contribute directly to the UN Sustainable Development Goals (SDGs) include: solar power technology (whose growth as a viable terrestrial energy source owes much to space-programme materials research); Earth-observation and remote-sensing systems that support agricultural planning and famine early-warning; satellite telecommunications that extend connectivity to remote and underserved regions; space-enabled education tools; and disaster-management systems that materially reduce loss of life. Advances in closed-loop life-support systems developed for long-duration missions likewise offer transferable lessons in resource recycling for terrestrial sustainability efforts. Satellite imagery and navigation systems additionally support national security objectives, from counter-terrorism to border control and search-and-rescue operations.[8]

3. The Environmental Cost of Space Activity

3.1 Space Debris

Space debris, also called space junk or orbital debris, comprises defunct human-made objects, principally in Earth orbit, that no longer serve any function.[9] It is widely regarded as the most

[7] ibid.

[8] Kalea Texeira, "The Impact of Space Exploration on Society: The Importance of Education and Public Engagement" https://www.linkedin.com/pulse/impact-space-exploration-society-importance-education-kalea-texeira-p4eec accessed 18/4/24; ESA (co-sponsored by the International Academy of Astronautics), "The Impact of Space Activities upon Society" https://www.esa.int/esapub/br/br237/br237.pdf accessed 17/4/24.

[9] Powell J, *Cosmic Debris* (Astronomers' Universe, Springer 2017), DOI: 10.1007/978-3-319-51016-3; UNOOSA, "Compendium: Space Debris Mitigation Standards Adopted by States and International Organizations"

pressing environmental problem generated by space activity, both because of its scale and because, unlike most forms of terrestrial pollution, it is largely self-perpetuating: each collision generates further debris, which in turn raises the probability of subsequent collisions.[10]

The physics make the danger acute. Any object in LEO travels at roughly 7.5 km/s, about ten to twenty times the speed of a rifle bullet; where two objects approach each other on intersecting orbits, relative closing speeds average around 10 km/s.[11] At such velocities, a fragment the size of a blueberry carries the destructive force of a falling anvil, and objects as small as one centimetre can disable, or, depending on mass ratio, destroy outright, an operational satellite.[12] The growing quantity of satellites and debris in LEO further contributes to light pollution that measurably degrades ground-based astronomy.

As of late 2022, the U.S. Space Surveillance Network tracked more than 25,000 artificial objects in orbit, including over 5,000 operational satellites. These figures capture only debris large enough to be catalogued; millions of smaller, untracked fragments pose an additional, uncharacterized risk.

The most consequential debris-generating events to date remain the 2009 collision between the active Iridium 33 satellite and the defunct Russian Cosmos 2251, and China's 2007 anti-satellite (ASAT) test against its own Fengyun-1C weather satellite. The Iridium–Cosmos collision, the first known hypervelocity collision between two intact satellites, occurred at a closing speed of roughly 11.7 km/s and, within months, had added more than 1,800 newly catalogued fragments larger than 10 cm to the U.S. Space Surveillance Network's tracking database, representing close

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https://www.unoosa.org/documents/pdf/spacelaw/sd/Space_Debris_Compendium_COPUOS_8_Apr_2021.pdf accessed 18/4/24.

[10] ibid.

[11] The Aerospace Corporation, "Space Debris 101" https://aerospace.org/article/space-debris-101 accessed 11/7/26.

[12] ibid; Kevin Barry, "Space Debris Mitigation and Remediation: Historical Best Practices and Lessons Learned for Economically Preserving and Utilizing Common Areas" (2022) *New Space* 10(3) 246, https://www.liebertpub.com/action/showCitFormats?doi=10.1089%2Fspace.2021.0022 accessed 18/4/24.

to ten percent of the entire tracked satellite population at the time.[13] China's Fengyun-1C test, for its part, generated more than 3,400 trackable fragments larger than 10 cm.[14] Together, these two events increased the cumulative number of tracked objects in orbit by more than a third.[15]

Natural cleansing mechanisms like atmospheric drag and luni-solar gravitational perturbation, offset some of this accumulation, but current annual launch rates (on the order of 100 or more per year) and continuing fragmentation events mean the debris population will keep growing. Because collision probability rises roughly with the square of the object count, doubling the number of tracked objects in a given orbital shell is expected to raise collision risk by a factor of approximately four.[16] Even a complete moratorium on new launches would not halt this growth in the near term, since existing debris continues to fragment; the resulting runaway cascade of collisions is known as the Kessler Syndrome, after the NASA scientist who first modelled it.[17][18]

While the probability of debris striking a person on Earth is low, controlled de-orbiting of larger objects carries its own environmental risk. The so-called "spacecraft cemetery" at Point Nemo (a remote area of the South Pacific roughly 3,000 miles from the nearest land, beyond any state's

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[13] NASA Orbital Debris Program Office, "Satellite Collision Leaves Significant Debris Clouds," *Orbital Debris Quarterly News* 13(2) (April 2009) 1, https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv13i2.pdf accessed 11/7/26; see also "2009 satellite collision" Wikipedia, citing U.S. Space Surveillance Network cataloguing figures. [Note: figures vary slightly by source and by date of count — the original manuscript cited >200,000 fragments >1cm and 3,273 trackable fragments >10cm; NASA ODPO's contemporaneous count was approximately 1,800 newly catalogued fragments >10cm within weeks of the collision, rising over subsequent years. Please confirm the exact figures you wish to use against the primary NASA ODPO source before submission.]

[14] NASA Orbital Debris Program Office, *Orbital Debris Quarterly News* (January 2013), discussing the sixth anniversary of the Fengyun-1C ASAT test; see also Space.com, "Worst Satellite Breakups in History: We're Still Feeling Effects" https://www.space.com/19450-space-junk-worst-events-anniversaries.html accessed 11/7/26.

[15] ibid (reporting that the two events together accounted for more than a third of the cataloged LEO satellite population).

[16] ESA, "About Space Debris" https://www.esa.int/Space_Safety/Space_Debris/About_space_debris accessed 18/4/24.

[17] NASA, "Micrometeoroids and Orbital Debris (MMOD)" https://www.nasa.gov/centers-and-facilities/white-sands/micrometeoroids-and-orbital-debris-mmod/ accessed 18/4/24.

[18] The Kessler Syndrome is named for NASA scientist Donald J. Kessler, who first modelled collisional cascading in the 1970s following the unexplained break-up of derelict Delta rocket stages left in orbit.

jurisdiction), has received more than 260 controlled splashdowns of decommissioned spacecraft from Russia, the United States, Japan, and several European states since 1971.[19][20] Although uninhabited by humans, this region hosts marine ecosystems that may be vulnerable to the toxic propellant residues and, in some cases, radioactive materials carried by de-orbited hardware.[21]

3.2 Contamination of Celestial Bodies

A second environmental concern operates in the opposite direction: the risk that Earth-based microorganisms, carried on spacecraft, could contaminate other celestial bodies and compromise the scientific search for indigenous or extant extraterrestrial life. The COSPAR Planetary Protection Policy addresses this risk directly, but it is narrowly scientific in scope, concerned with forward contamination of scientifically significant sites and backward contamination of Earth by returned extraterrestrial material, and does not extend to the broader environmental footprint of human space activity more generally.[22][23]

3 Atmospheric and Chemical Pollutants

Beyond debris and contamination, launch activity itself carries direct atmospheric costs. Since 2021, commercial space travel has expanded rapidly, led by SpaceX, Blue Origin, and Virgin Galactic; the latter alone conducted three successful commercial spaceflights between June and September 2023 and has flown more than sixteen private travellers.[24] One conservative business-

[19] Kevin Barry (n 12).

[20] Ferreira-Snyman A (n 3) 3.

[21] De Lucia and Iavicoli, *Cal W Int'l LJ* 345, 369, discussed in Ferreira-Snyman A (n 3) 14.

[22] André Galli and Andreas Losch, "Beyond planetary protection: What is planetary sustainability and what are its implications for space research?" PMID: 31791603, DOI: 10.1016/j.lssr.2019.02.005, https://pubmed.ncbi.nlm.nih.gov/31791603/ accessed 13/4/24.

[23] Qijia Zhou, "The UN's Role in Planetary Protection" *Harvard International Review* (2022) https://hir.harvard.edu/the-uns-role-in-planetary-protection/ accessed 13/4/24.

[24] Yize Wu, Kang-Lin Peng, Yijing Yao and Yanping Guo, "Sustainable Space Travel: What Can We Do in Education from Economic and Environmental Perspectives?" (2024) 16(2) *Sustainability* 684, DOI: 10.3390/su16020684, accessed 13/4/24.

strategy analysis estimates the net present value of the suborbital space-tourism market alone at upward of USD 2 billion.[25]

This growth carries environmental costs that scale with launch frequency. Black soot from incomplete combustion of rocket fuel is estimated to reduce local stratospheric temperatures by as much as 0.7°C while raising average Antarctic temperatures by roughly 0.8°C, and can persist in the stratosphere for five to ten years.[26] Carbon dioxide emissions from launches add to this burden. SpaceX's Dragon 2 capsule, for example, uses a nitrogen tetroxide (NTO)/monomethylhydrazine (MMH) bipropellant combination; MMH is a well-documented groundwater contaminant, and researchers have had to develop dedicated remediation techniques, such as composite-material activators, to clean up MMH-contaminated sites.[27] NTO's decomposition product, nitrogen dioxide, is itself a significant atmospheric pollutant implicated in tropospheric ozone formation. More than 2,460 solid rocket-motor firings to date have additionally released aluminium oxide as micrometre-sized dust and slag particles, now recognized as the most important source of non-fragmentation orbital debris.[28]

These harms are not irreversible if addressed early. Satellite Earth-observation data has itself documented glacial retreat, deforestation, ozone depletion, and desertification driven by human activity,[29] and the recovery of the ozone layer following the phase-out of chlorofluorocarbons, projected to return atmospheric ozone to pre-1980 levels by around 2030, demonstrates that

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[25] Guerster M, Crawley E and de Neufville R, "Commercial viability evaluation of the suborbital space tourism industry" (2019) 7 *New Space* 79, DOI: 10.1089/space.2018.0038.

[26] Ross M, Mills M and Toohey D, "Potential climate impact of black carbon emitted by rockets" (2010) 37 *Geophys. Res. Lett.* L24810, DOI: 10.1029/2010GL044548.

[27] Qian J, Ma R, Chen Z, Wang G, Zhang Y, Du Y, Chen Y, An T and Ni B-J, "Hierarchical Co-Fe layered double hydroxides (LDH)/Ni foam composite as a recyclable peroxymonosulfate activator towards monomethylhydrazine degradation" (2023) 469 *Chem. Eng. J.* 143554, accessed 16/4/24.

[28] ESA, "About space debris" (n 16).

[29] Li J, Pei Y, Zhao S, Xiao R, Sang X and Zhang C, "A review of remote sensing for environmental monitoring in China" (2020) 12 *Remote Sens.* 1130, accessed 16/4/24.

coordinated regulatory action can reverse even large-scale atmospheric damage.[30] The lesson for the space sector is that early, binding intervention is more effective, and less costly, than remediation after the fact.

4. Legal and Institutional Gaps

4.1 No Binding Definition of "Space Debris"

No space treaty currently supplies a legally binding definition of "space debris." Article I(d) of the Liability Convention defines a "space object" only vaguely, as including "component parts of a space object as well as its launch vehicle and parts thereof."[31] Commentators disagree on whether size should determine an object's classification: whether, for instance, fragmented or microparticulate debris qualifies as a "space object" at all, and on whether a rocket that never reaches orbit, or an inactive satellite, falls within the Convention's scope.[32] This ambiguity also complicates the emerging effort to identify and protect sites of space heritage.

The Inter-Agency Space Debris Coordination Committee (IADC), in deliberations before UNCOPUOS, has proposed defining debris broadly as "all man-made objects, including fragments and elements thereof, in earth orbit or re-entering the atmosphere, that are non-functional", a definition that would sweep in everything from paint flakes to entire derelict satellites, but which carries no binding legal force.[33][34]

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[30] Singh A and Bhargawa A, "Atmospheric burden of ozone depleting substances (ODSs) and forecasting ozone layer recovery" (2019) 10 *Atmos. Pollut. Res.* 802, accessed 16/4/24.

[31] Convention on International Liability for Damage Caused by Space Objects (adopted 29 March 1972, entered into force 1 September 1972) 961 UNTS 187 (Liability Convention), art I(d).

[32] Diedericks-Verschoor and Kopal, *Introduction to Space Law* 128; Viikari, *Environmental Element in Space Law* 70; Mukherjee and Mokkapati, (2009) *Proceedings of the International Institute of Space Law* 285.

[33] Technical Report on Space Debris, UN Doc A/AC.105/720 (1999); IADC Space Debris Mitigation Guidelines (rev 2, 2020) https://orbitaldebris.jsc.nasa.gov/library/iadc-space-debris-guidelines-revision2.pdf.

[34] Schrogl, "Space and Its Sustainable Uses" 605.

4.2 The Weakness of Article IX

Article IX of the Outer Space Treaty (OST) requires states to conduct lunar and planetary exploration "so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter." Although debris is not mentioned by name, the provision can plausibly be read to encompass debris-related harm.[35] The difficulty is that Article IX is drafted in aspirational, general terms; it offers no operative definition of "harmful contamination" or "adverse changes," rendering it non-prescriptive and, in practice, weakly enforceable.[36]

4.3 Voluntary Guidelines and Their Distributive Consequences

In the absence of binding international regulation, debris mitigation currently rests on voluntary compliance with the UN Space Debris Mitigation Guidelines, endorsed by the General Assembly in 2007 following work by the Scientific and Technical Subcommittee of UNCOPUOS.[37][38] Although the guidelines have since been implemented through the domestic legal systems of states such as Russia, Japan, and Germany, they were deliberately not adopted as a binding General Assembly resolution.[39]

This choice carries real distributive consequences. A binding framework would have created a level playing field by establishing enforceable, common obligations regardless of a state's technical or financial capacity; it would have improved transparency and accountability in implementation; and — perhaps most importantly for emerging space-faring nations — it would have provided a structured basis for technical and financial cooperation between established and

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[35] Ferreira-Snyman A (n 3) 16.

[36] Sgrosso, *International Space Law* 132; Viikari, *Environmental Element in Space Law* 59–60; Chrysaki (2020) *Space Policy* 3.

[37] International Cooperation in the Peaceful Uses of Outer Space, GA Res 62/217, UN Doc A/RES/62/217 (2007) (Space Debris Mitigation Guidelines).

[38] Schrogl, "Space and Its Sustainable Uses" 606; UNOOSA (2010) https://www.unoosa.org/pdf/publications/st_space_49E.pdf.

[39] Preface to the Space Debris Mitigation Guidelines, iv; Ferreira-Snyman A (n 3) 16.

developing space actors.[40] As matters stand, developing states must either build unilateral debris-mitigation capacity from limited resources or rely on the discretionary goodwill of established space powers, with no binding mechanism compelling the latter's cooperation. Even had the guidelines been adopted as a formal resolution, it bears noting that General Assembly resolutions themselves carry only the status of non-binding recommendation — so the practical gap, while real, is narrower than a first reading might suggest.[41]

4.4 Enforcement Gaps for Private Actors

Article VI of the OST places responsibility on states for the space activities of both governmental and non-governmental entities operating under their jurisdiction, which in principle extends planetary protection obligations to private companies. In practice, however, relatively few states have enacted domestic legislation translating this general obligation into specific, enforceable planetary-protection requirements. COSPAR's detailed planetary-protection recommendations partially fill this gap as soft law which is capable of informing domestic legislation and adapting quickly to new scientific findings, without the multi-year ratification cycles that formal treaty amendment would require; bbut soft law of this kind remains, by definition, non-binding.[42]

4.5 New and Unresolved Frontiers

The proliferation of new commercial activities: aerospace prize competitions, space tourism, and proposals for lunar burial services, has raised fresh concerns about the protection of historically or scientifically significant sites. The visible "trains" of Starlink satellites crossing the night sky, for example, have measurably interfered with ground-based astronomical and satellite imagery, prompting astronomers to warn publicly of a regulatory "Wild West" in orbit unless

[40] Lyall and Larsen, *Space Law* 274; Mukherjee and Mokkapati (n 32) 287; Schrogl, "Space and Its Sustainable Uses" 605.

[41] See generally Schrogl (n 34), noting that even a formally adopted General Assembly resolution carries only recommendatory, non-binding status.

[42] Qijia Zhou (n 23).

governments, private operators, and the scientific community establish a shared framework for coordinating megaconstellation deployment.[43]

More broadly, planned human activity in space: base construction, waste handling, mining, in-situ resource utilization, traffic management for orbital assets, end-of-mission debris disposal, deployment of large radio telescopes, and the use and disposal of nuclear power sources, carries direct, indirect, and cumulative environmental consequences that current instruments were not designed to address.[44] As lunar and Martian exploration intensifies, and as asteroid-resource extraction moves from concept toward feasibility study, the absence of a coordinated global framework becomes a more, not less, urgent problem.

5. Consequences of Inadequate Planetary Protection

Failure to implement robust planetary protection carries consequences that extend well beyond any single mission:

1. The Kessler Syndrome - a self-sustaining cascade of orbital collisions that could render entire orbital shells unusable, discussed above at Section 3.1.
2. Contamination of extraterrestrial environments, compromising the scientific search for indigenous or past life and altering the integrity of environments that may never be recoverable to their original state.[45]
3. Backward contamination risk: This hazard, however small in current mission designs, that extraterrestrial material returned to Earth could pose to Earth's own biosphere.[46]

[43] Mike Wall, "Why SpaceX's Starlink Satellites Caught Astronomers Off Guard" Space.com (9 January 2020) https://www.space.com/spacex-starlink-satellites-megaconstellation-surprise-astronomers.html accessed 11/7/26.

[44] This list of direct, indirect, and cumulative impacts draws on Coustenis et al (n 4) and related planetary-protection literature discussing the environmental footprint of proposed lunar and Martian settlement activity. [Author's note: if the original source for this specific list is available in your reference manager, please substitute the precise citation here.]

[45] Coustenis et al (n 4).

[46] ibid.

4. Compromised scientific research: Contamination from Earth-based organisms or organic residues can generate false-positive or otherwise unreliable data, undermining the credibility of astrobiological findings.

5. Threats to Earth's own ecosystems: The mirror image of (c), where inadequate return-mission protocols pose risk to terrestrial ecosystems and public health.

6. Ethical concerns: The prospect of discovering extraterrestrial life raises distinct ethical questions about the preservation of environments that may hold intrinsic, not merely instrumental, value.[47]

7. Erosion of public trust: High-profile contamination incidents or debris-related failures risk damaging public confidence in space programmes generally, with downstream effects on funding and political support.

8. Legal and policy fragmentation: The absence of comprehensive, binding standards produces inconsistent practice across space-faring states and entities, a problem the existing treaty framework was not built to resolve.[48]

9. Public safety risk on Earth: Inadequate sterilization protocols for returning spacecraft could, in principle, expose terrestrial populations to extraterrestrial material of unknown biological character.[49]

Addressing these risks requires sustained commitment to implementing and enforcing planetary-protection standards — not as a one-off compliance exercise, but as an evolving discipline that keeps pace with the scientific and commercial frontier.

6. Existing Frameworks for Space Sustainability and Planetary Protection

[47] ibid.

[48] Ferreira-Snyman A (n 3).

[49] NASA planetary protection literature, discussed further at Section 6.2 below.

6.1 International Guidelines and Agreements

International attention to interplanetary contamination dates to 1958, when the UN Committee on the Peaceful Uses of Outer Space (UNCOPUOS) made its first recommendations on the subject, building on parallel work by the U.S. National Academy of Sciences' ad hoc Committee on Contamination by Extraterrestrial Exploration (CETEX).[50]

A. COSPAR's Planetary Protection Policy: The Committee on Space Research (COSPAR), an international body under the International Council for Science, is the internationally recognized authority on the implementation of Article IX of the OST.[51] Its Planetary Protection Policy, grounded in current peer-reviewed science and updated regularly, sets acceptable limits on microbiological contamination risk and requires space agencies to demonstrate a very low probability of unintended planetary impact or, in the event of impact, a correspondingly low probability of biological contamination.[52] The policy operates as soft law but is widely adopted, including by the European Space Agency.[53]

B. UN Space Debris Mitigation Guidelines: The United Nations Office for Outer Space Affairs (UNOOSA) provides non-binding guidelines aimed at minimizing collision risk, requiring measures such as spacecraft sterilization protocols and ongoing contamination monitoring.

C. The Outer Space Treaty (1967): Though drafted at a time when environmental protection was not high on the agenda of space-faring states, several OST provisions bear on the

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[50] National Academies of Sciences, Engineering, and Medicine, *The Goals, Rationales, and Definition of Planetary Protection: Interim Report* (National Academies Press 2017), DOI: 10.17226/24809, ch 2, https://nap.nationalacademies.org/read/24809/chapter/3 accessed 18/4/24.

[51] Viikari, *Environmental Element in Space Law* 12, discussed in Ferreira-Snyman A (n 3) 7.

[52] COSPAR, *Planetary Protection Policy* (2020) https://cosparhq.cnes.fr/assets/uploads/2020/07/PPPolicyJune-2020_Final_Web.pdf accessed 15/4/24.

[53] ESA, "Planetary Protection" https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Exploration/ExoMars/Planetary_protection accessed 15/4/24.

issue.[54] Article I declares that "the exploration and use of outer space, including the moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries . . . and shall be the province of all mankind" — a principle from which one can plausibly infer that both states and the private entities they authorize are barred from conducting space activities that inflict environmental harm on the shared interests of other states.[55] Article IX, discussed above, imposes the operative (if weakly enforceable) contamination-avoidance obligation. The Moon Agreement (1979), Article VII, goes further in language, requiring states to "prevent the disruption of the existing balance of [the Moon's] environment" and to "avoid harmfully affecting the environment of the earth through the introduction of extraterrestrial matter or otherwise" — but the Agreement has been ratified by only a small number of states, none of them major space powers.[56]

6.2 NASA's Planetary Protection and Sterilization Policy

NASA's first spacecraft-sterilization policy was adopted in 1959, following an ad hoc Space Science Board committee chaired by Joshua Lederberg, whose recommendations, communicated to NASA and the Advanced Research Projects Agency that September, led NASA Administrator T. Keith Glennan to confirm that the agency had adopted sterilization "to the extent feasible" for any craft intended to pass near or impact the Moon or other planets.[57] NASA formally adopted planetary-protection requirements for the Moon, Mars, and Venus in 1963; COSPAR followed in 1964 with an interim quantitative contamination-probability framework, revised in 1967 and

[54] Viikari (n 51), discussed in Ferreira-Snyman A (n 3) 6, 10.

[55] Ferreira-Snyman A (n 3) 6.

[56] Agreement Governing the Activities of States on the Moon and Other Celestial Bodies (adopted 5 December 1979, entered into force 11 July 1984) 1363 UNTS 3 (Moon Agreement), art VII. As of the time of writing, the Agreement had not been ratified by any major space-faring state.

[57] Meltzer M, *When Biospheres Collide: A History of NASA's Planetary Protection Programs* (NASA History Series, NASA SP-2011-4234) https://www.nasa.gov/wp-content/uploads/2015/04/607072main_whenbiospherescollide-ebook.pdf accessed 11/7/26.

again in 1984, when the current category-based system (governing distinct requirements for orbiters, landers, and sample-return missions) was introduced.[58] The policy addresses two distinct risks: forward contamination, the transfer of Earth organisms to other bodies, and backward contamination, the transfer of extraterrestrial material to Earth.[59]

Collectively, these policies have had real, if partial, success in constraining the worst environmental harms of space activity. Their limitation is structural rather than technical: none of them binds states or private actors with the force of treaty law, and none carries a meaningful enforcement mechanism. The following section considers whether technological innovation can close some of that gap even where law has not.

7. Innovative Approaches to Space Sustainability

Space exploration can be made materially more sustainable through green propulsion, reusable launch systems, active debris mitigation, and rigorously enforced planetary-protection protocols. None of these substitutes for binding regulation, but together they narrow the gap between current practice and what regulation, if it existed, would require.

7.1 Green Propulsion and Eco-Friendly Spacecraft Design

Electric and solar-electric propulsion systems reduce mission emissions and, in many cases, launch costs, making space activity simultaneously cleaner and more accessible. Space agencies are increasingly building environmental-impact assessment into spacecraft design from the outset rather than treating it as an afterthought.

ESA's Clean Space Initiative, launched in 2012, is organized around three pillars:

i. *EcoDesign*, which applies life-cycle assessment methodology to minimize environmental impact across a mission's full lifecycle; a genuinely difficult optimization problem, since

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[58] National Academies Press (n 50); National Academies of Sciences, Engineering, and Medicine, *Preventing the Forward Contamination of Mars* (2006) ch 2, https://www.nationalacademies.org/read/11381/chapter/4 accessed 11/7/26.

[59] NASA Office of the Chief Engineer, "Implementing Planetary Protection Requirements for Space Flight," NASA-STD-8719.27 https://standards.nasa.gov/standard/NASA/NASA-STD-871927 accessed 18/4/24.

reducing impact at one stage (e.g., manufacturing) can inadvertently increase it at another (e.g., end-of-life disposal). ESA's GreenSat study, first tendered in 2016 and building on the agency's 2009 ECOSAT pilot work, is the first initiative worldwide dedicated to eco-designing a satellite mission from concept through disposal, and has since informed life-cycle assessments of operational missions including Sentinel-3 and PROBA-V.[60]

ii. *End-of-life management*, including active debris removal and "design-for-demise" spacecraft engineered to burn up completely on re-entry.

iii. *In-orbit servicing*, demonstrating the technical feasibility of extending or repairing defunct spacecraft in place, reducing the need for full replacement missions.

NASA's greener-propulsion efforts include continued use of liquid hydrogen, which offers a specific impulse roughly 30-40 percent higher than most conventional propellants and is comparatively environmentally benign, though its low density and cryogenic storage requirements limit its practicality in first-stage boosters.[61] NASA has also invested in green propellant alternatives to hydrazine, such as hydroxylammonium nitrate-based formulations, which offer lower toxicity, easier handling, and, in several formulations, improved performance.[62]

7.2 The Private Sector: Reusability and Its Limits

Reusable rockets and spacecraft reduce the environmental cost of each additional mission by eliminating the need to manufacture new hardware for every launch. SpaceX has demonstrated this at scale with its Falcon 9 booster; its Starship programme, intended for missions to the Moon

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[60] ESA, "Clean and eco-friendly space" https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/Clean_and_eco-friendly_space accessed 11/7/26; ESA, "GreenSat: one step closer to an environmentally friendly space mission" https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/Greensat_one_step_closer_to_an_environmentally_friendly_space_mission accessed 11/7/26.

[61] "Types of Rocket Fuel: From Hydrazine Rocket Fuel to Green Propellants" https://space4peace.org/types-of-rocket-fuel-from-hydrazine-rocket-fuel-to-green-propellants/ accessed 11/7/26.

[62] NASA White Sands Test Facility, "Green Propellants" https://www.nasa.gov/centers-and-facilities/white-sands/green-propellants/ accessed 11/7/26.

and Mars, extends the same logic to a fully reusable heavy-lift vehicle. Starship's promise is real, but so are its open environmental questions: its methane–oxygen propellant combination carries its own greenhouse-gas footprint through production and potential leakage; landing-site selection on other bodies requires ecological assessment before, not after, the fact; and any future resource-extraction activity will need governance frameworks that do not yet exist.[63] Reusability lowers the marginal environmental cost of each launch but it does not, by itself, resolve any of these upstream questions.

7.3 Debris Mitigation, ISRU, and Life-Support Innovation

Active debris removal, design-for-demise engineering, and continually improving tracking and collision-avoidance systems together represent the most direct technical response to the Kessler Syndrome risk described in Section 3.1. In-situ resource utilization (ISRU) (using materials found on the Moon, Mars, or asteroids to support mission operations), reduces dependence on resupply launches from Earth and, correspondingly, their cumulative environmental cost. Closed-loop life-support systems that recycle water, air, and waste extend mission duration while reducing consumable payload mass, with direct analogues in terrestrial sustainable-design practice.

7.4 International Cooperation and the Artemis Accords

The Artemis Accords, the set of bilateral principles underpinning NASA's Artemis lunar programme, commit signatory states to peaceful, transparent lunar exploration, including obligations to share information about lunar activity and to minimize interference with lunar heritage sites.[64] The Accords represent a genuine, if partial, advance: they build cooperative norms outside the slow multilateral treaty process, but their bilateral structure has also drawn

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[63] See generally reporting on SpaceX Starship development and environmental review; [Author's note: if you have a specific source for the Starship environmental-impact discussion, please cite it directly here.]

[64] The Artemis Accords (2020) https://www.nasa.gov/artemis-accords/. Some states have criticized the Accords' bilateral structure and the exclusion of non-signatory states.

criticism for excluding states not party to them, raising the risk of a two-tier governance regime for the Moon.

7.5 Market-Based Instruments: The Space Sustainability Rating

The World Economic Forum's Space Sustainability Rating (SSR), developed with international partners and operated by eSpace (the EPFL Space Centre) since early 2022, offers a voluntary certification framework scoring operators on debris-mitigation practice, choice of orbit, collision-avoidance measures, and end-of-mission disposal planning.[65] Certified companies including Airbus, Astroscale, Lockheed Martin, and SpaceX among others, can use their rating to signal responsible practice externally without disclosing proprietary mission data.[66] The SSR builds on prior work by the IADC and the UN Guidelines for the Long-Term Sustainability of Outer Space Activities, and its central innovation is incentive alignment: it makes sustainability commercially visible in a market that has, until now, had few ways to reward it. Its limitation is equally clear: participation is voluntary, and it therefore functions best as a complement to binding regulation, not a substitute for it.

7.6 Public Education and Social-Ethics Frameworks

Several scholars have proposed frameworks for embedding sustainability into the social and behavioural dimensions of space activity. Toivonen has proposed a "social ethics of space travel" encompassing virtual-reality alternatives to physical space tourism, targeted environmental-protection measures, the development of global space law, and deliberate engagement with the values of the generation now entering the space workforce.[67] While VR cannot substitute fully for the experience of space travel, it may reduce the cumulative environmental cost of nature-

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[65] World Economic Forum, "World's First Space Sustainability Rating Launched" https://www.weforum.org/impact/world-s-first-space-sustainability-rating-launched/ accessed 15/4/24.

[66] ibid.

[67] Toivonen A, "New Space Tourism Sustainability as an Evolving Concept" (2023) 2 *Highlights Sustain.* 75, DOI: 10.54175/hsustain2020007, accessed 15/4/24.

and space-based tourism by satisfying some of the underlying demand.[68] Peeters has argued, relatedly, that point-to-point regular space transport, rather than one-off tourism flights, represents the more sustainable long-term direction for the industry.[69]

8. Recommendations

The analysis above shows that technological innovation, while necessary, is not sufficient on its own to secure the long-term sustainability of space activity. This article therefore makes the following recommendations addressed to states, UNCOPUOS, and industry bodies:

i. **Adopt a binding treaty definition of "space debris."** UNCOPUOS should prioritize negotiating a protocol, or, at minimum, an authoritative interpretive instrument, that resolves the definitional gap in the Liability Convention, drawing on the IADC's existing working definition as a starting point.

ii. **Convert the UN Space Debris Mitigation Guidelines into a binding instrument**, phased in with differentiated compliance timelines for developing and emerging space-faring states, paired with a technology- and capacity-transfer mechanism funded by established space powers. This directly addresses the distributive concern identified in Section 4.3.

iii. **Require domestic implementing legislation for Article VI OST obligations.** States authorizing private space activity should be required to demonstrate, through periodic reporting to UNCOPUOS, that domestic law imposes enforceable planetary-protection and debris-mitigation requirements on licensed operators, closing the private-actor enforcement gap identified in Section 4.4.

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[68] Hoang SD, Dey SK, Tučková Z and Pham TP, "Harnessing the power of virtual reality: Enhancing telepresence and inspiring sustainable travel intentions in the tourism industry" (2023) 75 *Technol. Soc.* 102378, DOI: 10.1016/j.techsoc.2023.102378, accessed 15/4/24.

[69] Peeters W, "From suborbital space tourism to commercial personal spaceflight" (2010) 66 *Acta Astronaut.* 1625, DOI: 10.1016/j.actaastro.2009.10.026, accessed 15/4/24.

iv. **Mandate end-of-mission disposal planning as a licensing condition.** National space agencies and licensing authorities should require demonstrated post-mission disposal plans (de-orbit, graveyard orbit, or design-for-demise) as a precondition for launch licensing, building on, but making mandatory, the voluntary approach of the Space Sustainability Rating.

v. **Establish a multilateral coordination mechanism for megaconstellations**, addressing orbital slot allocation, light-pollution mitigation, and data-sharing obligations before deployment scale forecloses cooperative solutions, in response to the concerns raised in Section 4.5.

vi. **Extend the Artemis Accords' transparency norms multilaterally.** Rather than treating the Accords' cooperative principles as the property of a signatory bloc, UNCOPUOS should explore incorporating comparable transparency and heritage-site protection norms into a universal instrument open to non-signatory states.

vii. **Fund independent capacity-building for developing space-faring states**, particularly in space situational awareness and debris tracking, through a dedicated multilateral facility rather than ad hoc bilateral arrangements: a step that would also serve Africa's growing community of space agencies, including Nigeria's, as they scale up national space programmes.

9. Conclusion

As humanity pursues increasingly ambitious missions to the Moon, Mars, and beyond, the tension between commercial and scientific ambition on one hand, and environmental preservation on the other, will not resolve itself. The evidence surveyed in this article suggests that the existing legal architecture built substantially in the 1960s and 1970s, before debris, megaconstellations, or commercial space tourism existed at meaningful scale, has not kept pace with the environmental risks that contemporary space activity generates. Voluntary guidelines and soft-law instruments have achieved real, measurable progress, but their non-binding character leaves both the sustainability of the orbital environment and the equity of access to it dependent on the discretionary goodwill of the states and companies best positioned to exploit space first.

Technological innovation: green propulsion, reusable launch systems, active debris removal, and market-based instruments like the Space Sustainability Rating narrows this gap without closing it. Binding international regulation, developed in tandem with these technologies rather than trailing behind them, offers the only durable path to reconciling scientific and commercial ambition with the preservation of outer space as, in the language of the Outer Space Treaty, the "province of all mankind." The states and institutions that shape the next generation of space law have a narrow window in which to act before the orbital environment's carrying capacity, and the equitable distribution of access to it, are foreclosed by default rather than secured by design.

Recommendations

a. Governments should work through the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) and other international organizations to establish legally binding environmental standards for space activities. These standards should include stricter regulations on space debris mitigation, mineral exploitation and mining waste and pollution, satellite end-of-life disposal, responsible resource utilization, and environmental impact assessments for major space missions.

b. National governments and space agencies should increase investment in environmentally friendly mineral and mining systems, reusable consumables, utility vehicles with low-emission fuels, and energy-efficient spacecraft manufacturing technologies. Financial incentives, research grants, and public-private partnerships should be introduced to accelerate the development and adoption of green space technologies that reduce environmental footprints.

c. Stricter enforcement of Environmental Impact Assessments regulations and standards should become a compulsory requirement for all major space missions, mining facilities, and infrastructure development. These assessments should evaluate potential effects on terrestrial ecosystems, atmospheric conditions, biodiversity, and orbital sustainability before project approval, ensuring that environmental risks are minimized throughout the project lifecycle.

d. Governments and international regulatory bodies should enforce comprehensive debris mitigation measures, waste and pollution management systems, including mandatory satellite deorbiting plans, active debris removal technologies, collision avoidance systems, and compliance monitoring for both public and private space operators. International cooperation should also be enhanced to develop shared orbital traffic management systems that preserve the long-term usability of Earth's orbital environment.

e. Countries should incorporate environmental sustainability principles into national space policies, strategic plans, and educational programmes. This should include promoting interdisciplinary research on sustainable space exploration, strengthening environmental monitoring through satellite technologies, building institutional capacity for sustainable space governance, and increasing public awareness of the environmental implications of expanding space activities. Such integration will ensure that scientific innovation contributes simultaneously to economic development, environmental conservation, and the achievement of the Sustainable Development Goals (SDGs).